Charmed Hadrons from Strangeness-rich QGP

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Abstract. The yields of charmed hadrons emitted by strangeness rich QGP are evaluated within chemical non-equilibrium statistical hadronization model, conserving strangeness, charm, and entropy yields at hadronization.

1. Introduction

A relatively large number of hadrons containing charm and bottom quarks are expected to be produced in heavy ion (AA) collisions at the Large Hadrons Collider (LHC). Because of their large mass $c, \bar{c}$ quarks are produced predominantly in primary parton-parton collisions [1], at RHIC [2], and thus even more so at LHC. These heavy flavor quarks participate in the evolution of the dense QCD matter from the beginning. In view of the recent RHIC results it can be hoped that their momentum distribution could reach approximate thermalization within the dense QGP phase [3].

We study in this report heavy quark hadronization, and we are particularly interested in how strangeness influences heavy and multi-heavy hadron yields (containing more than one heavy quark). In the presence of deconfined QGP multi-heavy hadrons are formed from heavy quarks created in the initial NN collisions. Therefore yields of these hadrons are expected to be enhanced as compared to yields seen in single NN collisions [4, 5]. This type of enhancement can be considered to be an indicator of the presence of deconfined QGP phase, for reasons which are analogous to those given in the context of multi-strange (anti) baryon enhancement [6]. $J/\Psi(c\bar{c})$ yields were for this reason obtained in the kinetic formation and dissociation model [4, 7] but without consideration of a strangeness content in the QGP phase.

Differing from other recent studies which assume that the hadron yields after hadronization are in chemical equilibrium [5, 8], we obtain the charm hadron yields in the statistical hadronization approach based on an abundance of u, d, s quark pairs fixed by the bulk properties of a chemically equilibrated QGP phase. Since we do not yet know to sufficient precision the heavy flavor production at LHC or even RHIC energies, we present particle yields normalized by the total charm flavor yield, such that the particle yield results we consider are little dependent on the unknown total yield of charm. The results we present were obtained for $dN_c/dy \equiv c = 10$.

2. Fast Hadronization

We study within the statistical hadronization model (SHM) the charmed hadron production at fixed strangeness pair yield per entropy s/S. This in general requires the chemical non-equilibrium version of the SHM. The important parameters of the SHM, which control the relative yields of particles, are the particle specific fugacity factor λ and space occupancy factor γ. The fugacity is related to chemical potential $\mu = T\ln\lambda$. We take $\lambda_i = 1$ for all flavors since the small particle-antiparticle yield asymmetry at RHIC and LHC is not relevant here.

The ratio of the number of given type particles produced, to the number expected in chemical equilibrium is (nearly) the phase space occupancy γ, which is the same for particles and antiparticles of the type considered. We use occupancy factors $\gamma_i^{\rm Q}$ and $\gamma_i^{\rm H}$ for QGP and hadronic gas phase respectively, tracking every quark flavor (i = q, s, c). For each hadron, the phase space occupancy $\gamma^{\rm H}$ is the product of $\gamma^{\rm H}$'s for each constituent quark. For example for the charmed meson D($c\bar{q}$), $\gamma_D^{\rm H} = \gamma_c^{\rm H}\gamma_q^{\rm H}$. The value of $\gamma_q^{\rm H}$ has upper limit arising from the condition of Bose-Einstein condensation of pions $\gamma_\pi = \gamma_q^2 \leq e^{m_\pi/T}$.

The number of particles of type 'i' with mass m_i per unit of rapidity is:

$$\frac{dN_i}{dy} = \gamma_i n_i^{\rm eq}\frac{dV}{dy}. \tag{1}$$

Here dV/dy is system volume associated with the unit of rapidity, and $n_i^{\rm eq}$ is a Boltzmann particle density in chemical equilibrium:

$$n_i^{\rm eq} = g_i \int \frac{d^3p}{(2\pi)^3}\lambda_i \exp(-\sqrt{p^2+m_i^2}/T) = \lambda_i\frac{T^3}{2\pi^2}g_i(m_i/T)^2K_2(m_i/T). \tag{2}$$

During a fast transition between QGP and HG phases strange and heavier quark flavor yields are preserved, as are the entropy per unit of rapidity [9], and the specific, per rapidity, hadronization volume:

$$\frac{dN_i^{\rm H}}{dy} = \frac{dN_i^{\rm Q}}{dy} = \frac{dN_i}{dy},\ \ i = s, c; \quad \frac{dS^{\rm H}}{dy} = \frac{dS^{\rm Q}}{dy} = \frac{dS}{dy}; \quad \frac{dV^{\rm Q}}{dy} = \frac{dV^{\rm H}}{dy}. \tag{3}$$

The yields of hadrons after hadronization are given by Eq. (1), the three unknown $\gamma_q^{\rm H}$, $\gamma_s^{\rm H}$ and $\gamma_c^{\rm H}$ can be determined from their values in the QGP phase, or equivalently corresponding flavor yields, i.e. $\gamma_i^{\rm Q}$ or dN_i^Q/dy given in Eq. (3). $\gamma_i \neq 1$ implies that hadron yields are in general not in a chemical equilibrium. We will show how this influences the relative yields of heavy flavored particles in the final state.

The number of strange quark pairs determines the value of $\gamma_s^{\rm H}$:

$$\frac{dN_s}{dy} = \frac{dV}{dy}\left[\gamma_s^{\rm H}\left(\gamma_q^{\rm H} n_K^{\rm eq} + \gamma_q^{{\rm H}\,2} n_Y^{\rm eq}\right) + \gamma_s^{{\rm H}\,2}(2\gamma_q^{\rm H} n_\Xi^{\rm eq} + n_{s\,\rm hid}^{\rm eq}) + 3\gamma_s^{{\rm H}\,3} n_\Omega^{\rm eq}\right], \tag{4}$$

where $n_i^{\rm eq}$ are densities of strange mesons and baryons calculated using Eq. (1) in chemical equilibrium, $n_{s\,\rm hid}^{\rm eq} = n_\phi^{\rm eq} + P_s n_\eta^{\rm eq}$ and P_s is the strangeness content of the η. The pattern of this calculation follows an established approach by using SHARE 1.2 program [10] in the calculation.

For charm hadrons $\gamma_c^{\rm H}$ is obtained from:

$$\frac{dN_c}{dy}=\frac{dV}{dy}\left[\gamma_c^{\rm H} n_{\rm op}^c+\gamma_c^{\rm H\,2}(n_{c\,\rm hid}^{\rm eq}+2\gamma_q^{\rm H} n_{ccq}^{\rm eq}+2\gamma_s^{\rm H} n_{ccs}^{\rm eq})\right]; \tag{5}$$

where open 'op' charm yield is:

$$n_{\rm op}^c=\gamma_q^{\rm H} n_D^{eq}+\gamma_s^{\rm H} n_{Ds}^{eq}+\gamma_q^{\rm H\,2}\, n_{qqc}^{\rm eq}+\gamma_s^{\rm H}\gamma_q^{H} n_{sqc}^{eq}+\gamma_s^{\rm H\,2}\, n_{ssc}^{\rm eq}; \tag{6}$$

Here $n_D^{\rm eq}$ and $n_{Ds}^{\rm eq}$ are densities of D and D_s mesons respectively in chemical equilibrium, $n_{qqc}^{\rm eq}$ is equilibrium density of baryons with one charm and two light quarks, $n_{qsc}^{\rm eq}$ is density of baryons with one light, one s and one c quarks, $n_{ssc}^{\rm eq}$ is density of baryons with one charm and two strange quarks ($\Omega_c^0(ssc)$) and $n_{c\,\rm hid}^{\rm eq}$ is the density of particles with both a charm quark and an anticharm quark (C=0, S=0).

The use of the hadron phase space (denoted by H above) does not imply the presence of a real physical 'hadron matter' phase: the SHM particle yields will be attained solely on the basis of availability of this phase space. In fast hadronization one can assume that there are practically only free-streaming particles in the final state.

Thinking in these terms, one can imagine that especially for heavy quark hadrons some particles are pre-formed in the deconfined plasma, and thus the heavy hadron yields may be based on a value of temperature which is higher than the global value expected for other hadrons. For this reason we will study in this work a rather wide range $140 < T < 260$ MeV.

We will use as a reference a QGP state with the ratio strangeness (s) to entropy (S) fixed. We take it be in the range s/S =0.03 – 0.04, and consider dV/dy =600 – 800fm^3 at $T = 200\,$MeV. This corresponds to total particles' multiplicity of about 4000–5000 after hadronization for T=140 MeV, according to calculations using SHARE 1.2 [10]. This is within the expected range of total hadron multiplicity per unit of rapidity for LHC. We compare our results to the 'benchmark' reference yield which is obtained using $\gamma_s^{\rm H}=\gamma_q^{\rm H}=1$ (chemical equilibrium).

3. Yields of charmed hadrons

3.1. D, D_s meson yields

Considering Eq. (1), and using γ_c^H, γ_s^H, γ_q^H at a given T we have now all the inputs required to compute relative particle yields of all charmed hadrons. In figure 1 we show in the upper panel the fractional yields of non-strange D/N_c and strange D_s/N_c charmed mesons normalized by the total number of charm quarks N_c as functions of hadronization temperature. The dashed lines are for chemical equilibrium. The extreme upper and lower lines are for $s/S = 0.03$ (purple, solid and dash-dot lines), while the central lines are for $s/S = 0.04$ (green, solid and dash-dot lines). We recall that the chemical equilibrium of strangeness in QGP corresponds to $s/S \simeq 0.03$. The yield of D is the sum over all $(\bar qc)$ states i.e. D^0 and D^+ ($D^+\approx D^0$) mesons and resonances. Similarly, $D_s(\bar sc)$ is the sum over all resonances of D_s mesons.

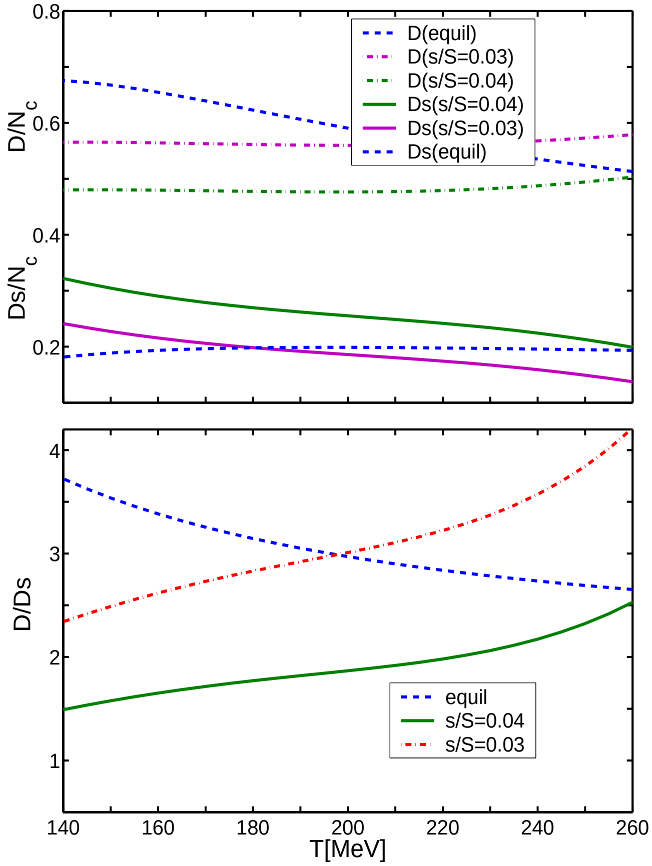

Figure 1. The upper panel: charm meson yield per total charm yield N_c. Equilibrium (dashed lines, blue), non-equilibrium (solid and dash-dot lines are for D_s and D, respectively). The lines for $s/S = 0.04$ (green) are more centrally located in each frame, outer (purple) lines are for $s/S = 0.03$. The lower panel: ratios D/D_s as a function of T. Solid line is for $s/S = 0.04$, dash-dot line is for $s/S = 0.03$, dashed line is for $\gamma_s^{\rm H} = \gamma_s^{\rm H} = 1$ (chemical equilibrium).

In the lower panel we show the ratios D/D_s as a function of hadronization temperature. There is a considerable deviation in the ratios obtained for a fixed s/S from the chemical equilibrium results, except for the accidental values of T where the equilibrium results (dashed line) cross the fixed s/S results. While the chemical equilibrium results show significant difference between strange and non-strange heavy mesons, for the fixed s/S case, with increasing s/S and towards low T these yields become nearly equal. If the heavy meson yields are established at temperatures similar to regular hadrons, relative enhancement by factor 2–2.5 in strange-heavy mesons is to be expected for LHC. For RHIC conditions ($s/S = 0.03$, $c = \bar{c} = 2$) D/D_s ratio is lower than the chemical equilibrium value for $T < 0.2$. This ratio decreases by factor of 1.6 for $T \rightarrow 140$ MeV.

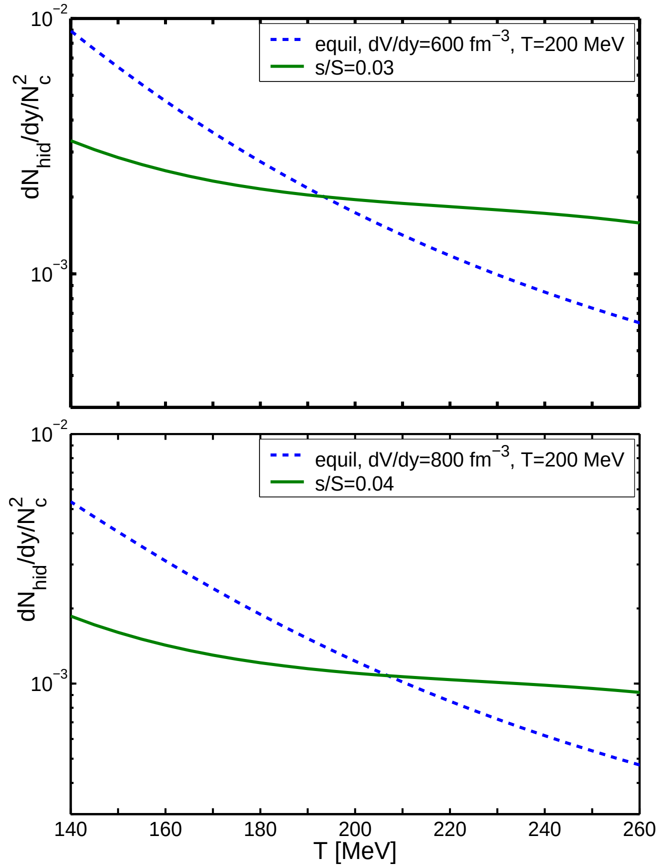

Figure 2. $c\bar{c}/N_c^2$ relative yields as a function of hadronization temperature T for $s/S = 0.03$ with reference volume $dV/dy = 600\,\mathrm{fm}^{-3}$ at $T = 200$ MeV (upper panel); and $s/S = 0.04$ with $dV/dy = 800\,\mathrm{fm}^{-3}$ at $T = 200$ MeV(lower panel). Dashed lines are for chemical equilibrium.

3.2. Yields of hadrons with two heavy quarks

The hadron yields with two heavy quarks are model dependent, being proportional to $1/dV/dy$ because γ_i^H for heavy quarks is proportional to $1/dV/dy$. Thus our result is dependent on the reaction volume, or on the total assumed charm yields. In figure 2 we show the yield of hidden charm $c\bar{c}$ (sum over all states of $c\bar{c}$) mesons normalized by the square of charm multiplicity N_c^2 as a function of hadronization temperature T for two different reference values of volume at $T = 200$ MeV: $dV/dy = 600\,\mathrm{fm}^3$ (upper panel), and $dV/dy = 800\,\mathrm{fm}^3$ (lower panel). We consider again cases with $s/S = 0.03$ (upper panel, solid line) and $s/S = 0.04$ (lower panel, solid line). For comparison, the chemical equilibrium $c\bar{c}$ mesons yields are shown (dashed lines on both panels). Entropy per unit of rapidity dS/dy is conserved, during cooling/expansion of the QGP, which implies $VT^3 \simeq$Const. In the second case considered rapidity density of strangeness is 78% higher than in the first.

The yield of $c\bar{c}$ mesons is much smaller at fixed $s/S = 0.04$ than in chemical equilibrium for the same dV/dy for large range of hadronization temperatures. For

$s/S = 0.03$ the effect is similar, but charmonium suppression is slightly less pronounced. This new mechanism of charmonium suppression occurs due to competition with the yield of strange-heavy mesons. The enhanced yield of D_s in effect depletes the pool of available charmed quark pairs, and fewer hidden charm $c\bar{c}$ mesons are formed. For particles with two heavy quarks the effect is larger than for hadrons with one heavy quark and light quark(s).

4. Conclusions

We have considered here the abundances of heavy flavor hadrons within the statistical hadronization model. While we compare the yields to the expectations based on chemical equilibrium yields of light and strange quark pairs, we present results based on the hypothesis that the QGP entropy and QGP flavor yields determine the values of phase space occupancy $\gamma_i^{\rm H}$, $i = q, s, c$, which are of direct interest in study of the heavy hadron yields.

We studied how the (relative) yields of strange and non-strange charmed mesons vary with strangeness content. For a chemically equilibrated QGP source, there is considerable shift of the yield from non-strange D to the strange D_s. Since the expected fractional yield $D_s/N_c \simeq 0.2$ when one assumes $\gamma_s^{\rm H} = \gamma_q^{\rm H} = 1$, one should be able to falsify chemical (non-)equilibrium hypothesis easily: the expected enhancement of the strange heavy mesons being at the level of 40% when $s/S = 0.03$, and yet greater, when greater strangeness yield is available.

Another consequence of this result is that we find a relative suppression of the multi-heavy hadrons, except when they contain strangeness. The somewhat ironic situation is that while higher charm QGP yield enhances production of $c\bar{c}$ states, the enhanced strangeness suppresses this effect.

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5. References

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